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Declutching control of a wave energy converter

Aurélien Babarit [a,*], Michel Guglielmi [b], Alain H. Clément [a]

[a] Laboratoire de Mécanique des Fluides (CNRS UMR6598), Ecole Centrale de Nantes, 1 Rue de la Noë, B.P. 92101, 44321 Nantes cedex 3, France

[b] Institut de Recherche en Communication et Cybernétique de Nantes (CNRS UMR6597), Ecole Centrale de Nantes, 1 Rue de la Noë, B.P. 92101, 44321 Nantes cedex 3, France

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ABSTRACT

When hydraulic power take off (PTO) is used to convert the mechanical energy of a wave energy converter (WEC) into a more useful form of energy, the PTO force needs to be controlled. Continuous controlled variation of the PTO force can be approximated by a set of discrete values. This can be implemented using either variable displacement pumps or several hydraulic cylinders or several high pressure accumulators with different pressure levels. This pseudo-continuous control could lead to a complex PTO with a lot of components. A simpler way for controlling this hydraulic PTO is declutching control, which consists in switching on and off alternatively the wave energy converter's PTO. This can be achieved practically using a simple by-pass valve. In this paper, the control law of the valve is determined by using the optimal command theory. It is shown that, theoretically when considering a wave activated body type of WEC, declutching control can lead to energy absorption performance at least equivalent to that of pseudo-continuous control. The method is then applied to the case of the SEAREV wave energy converter, and it is shown than declutching control can even lead to a higher energy absorption, both in regular and irregular waves.

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0. Introduction

Amongst the wide variety of wave energy converter (WEC) concepts that have been proposed, the class of so-called *wave activated bodies*, WECs, uses wave induced motions of masses or large bodies to drive a power take off (PTO) system which transforms the primary mechanical energy of the body into a final usable form, generally electricity. A lot of devices are based on this concept, such as for example the WRASPA (Chaplin and Aggidis, 2007), the SEAREV (Josset et al., 2007), or the Pelamis (Henderson, 2006) whose first units have been deployed into Scottish and Portuguese waters.

In many cases (Henderson, 2006, Josset et al., 2007), the PTO is hydraulic. It usually features one or several hydraulic cylinders, high pressure (HP) accumulators and a hydraulic motor which drives an electrical generator. Fig. 1 shows a typical hydraulic PTO system. This seems to be a reasonable option, at least at a prototype stage. There are many of the shelf hydraulic components from the marine and offshore industry that are capable of dealing with the large forces and slow motions usually occurring in wave energy conversion. Moreover, high pressures accumulators allow storage of the energy extracted from the waves, and thus contribute to the smoothing of the output power delivered to the grid.

When designing such hydraulic PTOs, it is necessary to include components allowing control of the force applied by the PTO to the prime mover of the wave energy converter. In contrast with the smooth continuous force applied by a linear damper, the force of a hydraulic PTO is a Coulomb damping. This means that its modulus is a constant equal to the area of the cylinder times the pressure difference between the high pressure and low pressure (LP) accumulators. When the pressure difference between the accumulators is too large, the PTO force can cancel the other external forces (including the wave excitation force), hence preventing any motion of the wave energy converter, which would result in a zero energy production. On the other hand, if the pressure difference is too small, the PTO force can become too small in comparison with what it should be to maximise the energy absorption or to keep the amplitude of the motion in an acceptable range.

These effects were observed by de Falcao (2007) on a generic heaving WEC and by Josset et al. (2007) on the SEAREV WEC. It was found by both authors that they can be counteracted using a slow control method consisting in adapting the pressure in the HP accumulator and the flow in the hydraulic motor to the sea state. By using this *sea state dependent control*, it was even found that the output power can sometimes exceed that of an optimised linear damping PTO. In de Falcao (2008), it is shown that phase control can successfully be achieved for a heaving buoy WEC with a hydraulic PTO using a similar sea state dependent control. In this case, the control consists in adapting the flow in the hydraulic motor and the flow from the hydraulic cylinder.

* Corresponding author.
E-mail addresses: aurelien.babarit@ec-nantes.fr (A. Babarit), michel.gulgliemi@irccyn.ec-nantes.fr (M. Guglielmi), alain.clement@ec-nantes.fr (A.H. Clément).

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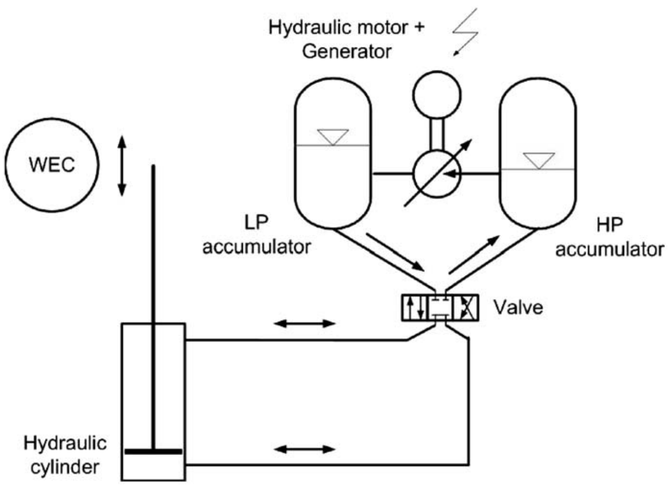

Fig. 1. Schematic representation of a hydraulic PTO for wave energy conversion.

By using several hydraulic cylinders and/or several HP accumulators with different pressure levels in the hydraulic PTO, it is also possible to control the PTO force in order to adapt it to each incoming wave and it is even possible to mimic a continuous behaviour, as it seems to be done in the Pelamis for example (Henderson, 2006). Later in this paper, this strategy for controlling the PTO force will be called *pseudo-continuous control*. In comparison with the sea state dependent control strategies, it brings a lot more complexity in the PTO, raising technical issues such as a possibly higher risk of failure.

As an alternative to this, we consider another strategy of *declutching control*, or unlatching as it was introduced by Salter et al. (2002). It consists in declutching the PTO—which means that the PTO force is set equal to 0—during some parts of the cycle. Technologically, it is very simple to implement, as it needs only a by-pass valve in the circuit of the hydraulic cylinder. This control has already been considered by Justino et al. (2000) for the Portuguese oscillating water column in Pico: the relief valve was intended to control the air flow through the Wells turbine in order to prevent it from exceeding the aerodynamic stall-free range, and in this way reduce aerodynamic losses in the turbine. However, it was not considered as a mean of controlling the PTO force.

There are many other ways of controlling the PTO force of a wave energy converter and one can refer to Salter et al. (2002) for an exhaustive review of all of them. However, we chose to focus here only on both pseudo-continuous control and declutching control because our aim is to show that, at least theoretically, pseudo-continuous control can be advantageously replaced by declutching control. Indeed, we show here that there is actually no need for a complex hydraulic PTO featuring several HP accumulators or several hydraulic cylinders as only one by-pass valve is conceptually sufficient in order to achieve at least the same level of energy absorption. This is shown theoretically in the first part of this paper by applying the optimal command theory to the generic equations of floating wave energy converters, including the hydraulic PTO. Then, the method is applied to the SEAREV WEC as an example, and theoretical results are confirmed.

1. Governing equations

1.1. Equation of motion

Let us consider a generic wave energy converter composed of one or several bodies moving under the action of incident waves. Let N_{dof} be the total number of degrees of freedom of this wave energy converter. Assuming the fluid to be non-viscid and incompressible, the flow to be irrotational and the amplitude of motions and waves to be sufficiently small compared to the wavelength, the classical linearised potential theory can be used as a framework for calculation of the fluid–structure interactions. Hence, one can write the equation of motion of the WEC in the time domain as

$$(\mathbf{M} + [\mu_\infty])\ddot{\mathbf{Y}} + \int_0^t \mathbf{K_{rad}}(t-\tau)\dot{\mathbf{Y}}(\tau)\,d\tau + (\mathbf{K}_H + \mathbf{K}_A)\mathbf{Y} = \mathbf{F}_{ex} + \mathbf{F}_{PTO} \quad (1)$$

with:

- $\mathbf{Y}, \dot{\mathbf{Y}}, \ddot{\mathbf{Y}}$ being, respectively, the generalised position, velocity, and acceleration vectors of the WEC.
- $\mathbf{M}$ the generalised mass matrix of the system.
- $\mathbf{K}_H$ the hydrostatic stiffness matrix of the system.
- $\mathbf{K}_A$ an additional stiffness matrix which represents the action of moorings.
- $[\mu_\infty]$ the added mass matrix and $\mathbf{K_{rad}}$ the radiation impulse response matrix which represents the radiation of waves by the body after an impulsive velocity at $t = 0$, according to the classical Cummins' (1962) decomposition. Using Prony's method (Duclos et al., 2001), one can further approximate each of the $K_{rad,kl}$ functions, components of $\mathbf{K_{rad}}$, by a sum of N_{kl} complex functions $K_{rad,kl}(t) = \sum_{j=1}^{N_{kl}} \sigma_{klj} \exp(i\beta_{klj} t)$. As a consequence of this approximation by series of exponential functions, each convolution product can be replaced by a sum of N_{kl} additional *radiative* complex states $\int_0^t K_{kl}(t-\tau)\dot{Y}_l(\tau)\,d\tau = \sum_{j=1}^{N_{kl}} I_{klj}$ with each I_{klj} given by an ordinary differential equation $\dot{I}_{klj} = \beta_{klj} I_{klj} + \sigma_{klj}\dot{Y}_l$. Finally, one can get
$$\int_0^t \mathbf{K_{rad}}(t-\tau)\dot{\mathbf{Y}}(\tau)\,d\tau = [\boldsymbol{\delta}]\mathbf{I}$$
$$\dot{\mathbf{I}} = [\boldsymbol{\beta}]\mathbf{I} + [\sigma]\dot{\mathbf{Y}} \quad (2)$$
with $\mathbf{I} = (I_{klj})_{1\le k\le N_{dof}, 1\le l\le N_{dof}, 1\le j\le N_{kl}}$. More details on this method can be found in Babarit and Clément (2006).
- $\mathbf{F}_{ex}$ is the excitation vector, associated to the action of incident and diffracted wave fields upon the WEC. Using King's (1987) approach, let $\mathbf{K}_{ex}(t)$ be the force response associated to an impulsive elevation on the free surface propagating along the x axis. Using the superposition principle, owing to the global linearity of the problem solved here, the generalised excitation force is then given by
$$\mathbf{F}_{ex}(t) = \int_0^t \mathbf{K}_{ex}(t-\tau)\eta(\tau)\,d\tau \quad (3)$$
with $\eta(t)$ being the free surface elevation at a given reference location. In case of regular wave, $\eta(t)$ is an elementary sine function $a\sin(\omega t + \varphi)$ with a the amplitude of the wave, ω its circular frequency, and φ an initial phase. In case of random waves, $\eta(t)$ will be considered here as a sum of N_c elementary sinus functions whose amplitudes $(a_j)_{j=1,N_c}$ are derived from the standard Pierson–Moskowitz energy spectrum Molin (2002) and whose phases $(\varphi_j)_{j=1,N_c}$ are set randomly.
- $\mathbf{F}_{PTO}$ is the force vector associated to the action of the power take off. If the PTO is a linear damper, $\mathbf{F}_{PTO}$ is given by
$$\mathbf{F}_{PTO} = \mathbf{B}_{PTO}\dot{\mathbf{Y}}$$
with $\mathbf{B}_{PTO}$ being the PTO damping coefficient matrix.

1.2. Equation for the PTO

A linear damper is the classical basic approach for modelling the PTO of a wave energy converter, leading to a global solution of the equation of motion in the frequency domain. But in the real

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